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MAGNETORESISTANCE AND HALL EFFECT OF Mn-DOPED SnTe USING SUPERCONDUCTING MAGNET

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(Abstract) Using a 40 kG superconducting magnet, we have reinvestigated the resistivity and Hall effect for Mn-doped SnTe crystals. In this degenerate semiconductor there appears a ferromagnetic ordering at some low temperature T_m. Negative magnetoresistance is observed only around a limited range of temperature near T_m, while the extraordinary Hall effect similar to ferromagnets can been seen below the ordering temperature.

1. INTRODUCTION

It has been made clear that the localized spins of magnetic impurity dissolved in a degenerate semiconductor such as SnTe manifest themselves a weak ferromagnetic ordering at a low temperature. The magnetic ordering temperature is primarily determined by a ferromagnetic or paramagnetic Curie temperature from the inverse susceptibility vs temperature curve. Our previous experiments[1,2] on Mn-doped SnTe crystals show a resistivity maximum, negative magnetoresistance and anomalous Hall effect around the ordering temperature, which depends on the number of the magnetic impurities. In this work we have further attempted to reinvestigate the above phenomena using a commercial superconducting magnet.

2. EXPERIMENTAL

The sample used were the same as the previous ones. Thus far the electrical measurements have been carried out by a point-to-point procedure using a dc potentiometer, a magnetic field being produced by an electromagnet attainable up to 21.5 kG. In the present experiment , the magnetic field was produced by a commercial superconducting magnet (bore 30 mm, length 21 cm, maximum field 40 kG, manufactured by Vacuum Metallurgical Co.) equipped with a regulated current source;

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the exciting current can be changed manually or automatically at a rate of 5A/min so that the sample voltages against the field strength could be recorded on an X-Y recorder. The magnet was immersed in liquid helium contained in a home-made metal dewar. A typical field distribution along the axis of the solenoid is illustrated in Fig. 1, where

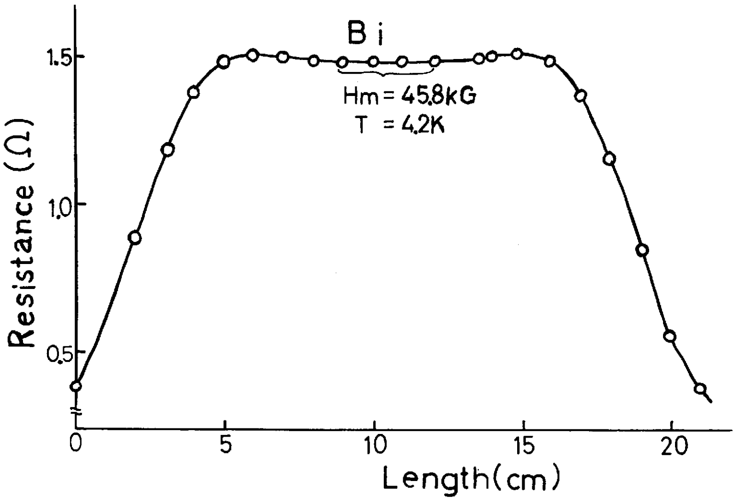

Fig. 1. Field distribution along the axis of the superconducting solenoid at 45.8 kG; the resistance of a polycrystalline bismuth needle is plotted against the position.

the resistance of a polycrystalline bismuth needle as a field sensor is plotted as a function of the position at 45.8 kG. A fairly good homogeneity (0.01 %/$\pm$15 mm) is available over 3 cm around the central part.

The cryostat used for the electrical measurements was of a conventional type as shown in Fig. 2. The sample was placed on the bottom of a copper holder and an Allen-Bradley carbon resistor was attached in a hole drilled close to the sample. A manganin heater was wound around the upper part of the copper block and the lead wires were all in contact with a thermal anchor. The cavity was put in the center of the superconducting solenoid. Above 4.2 K the cavity was kept at 10^{-5} Torr vacuum when the heater was switched on, while below 4.2 K the entire liquid helium bath was evacuated by a mechanical pump and the vapor pressure was regulated by a manostat.

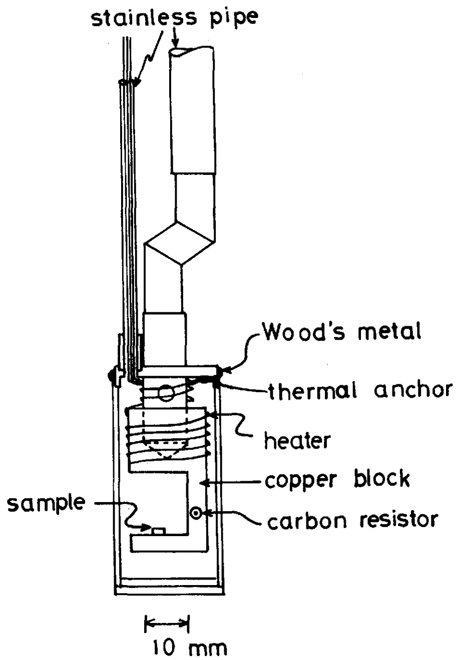

Fig. 2. A cryostat for the electrical measurements.

3. RESULTS AND DISCUSSION

As noted thus far,[1,2] it is certain that there exists a localized-spin-dependent scattering of conduction carriers in the Mn-doped SnTe crystals as in dilute alloys. So far as the electrical resistivity is concerned, however, it is of interest to note that in the resistivity vs temperature curve the resistivity maximum of the present system is rather narrow and small compared with those of the metallic alloys, and with increasing carrier concentration the resistivity maximum tends to disappear, with only a monotonic decrease in the resistivity with the lowering of temperature. This may suggest that the spin-dependent contribution is only effective over a restricted range of temperature.

The experimental results for a sample with carrier concentration $p=2.1 \times 10^{20}$ cm^{-3} and 0.88 at.% Mn are shown in Fig. 3. The resistivity maximum of this sample is hardly seen, and the magnetic ordering temperature T_m is estimated to be about 5 K. The transverse magneto-resistance is negative when the temperature is in the vicinity of T_m, while at lower temperatures it becomes positive. This is the case also at higher temperature, as illustrated in Fig. 4, where the recorded traces at 4.2 and 12 K are shown for the same sample.

Another aspect of the spin-dependent transport properties is the Hall effect. In Fig. 5 are shown several recorded traces of the Hall

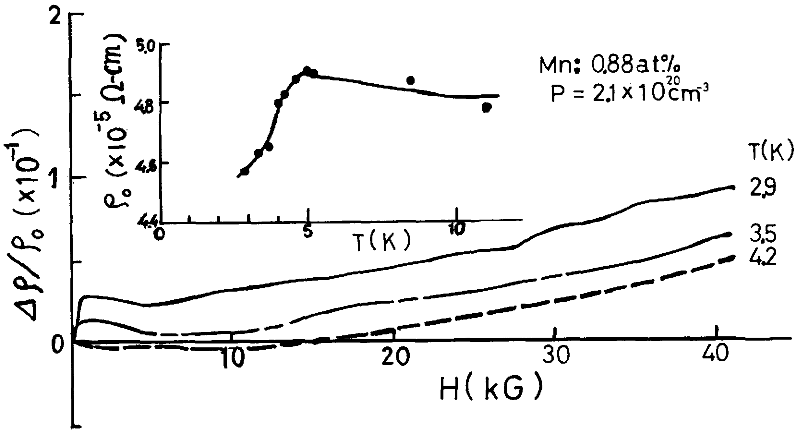

Fig. 3. The transverse magnetoresistance at different temperatures and the temperature dependence of the resistivity (insert) for a typical Mn-doped SnTe crystal.

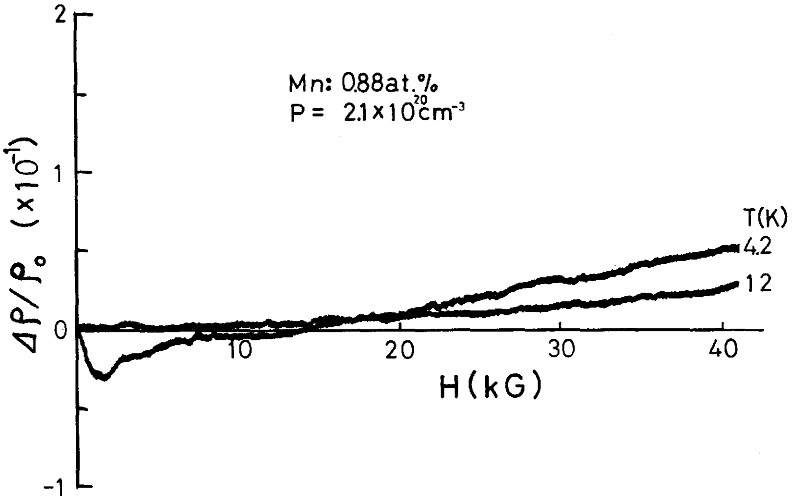

Fig. 4. The magnetoresistance against applied field at 4.2 and 12 K for the same sample as in Fig. 3.

voltage against the magnetic field for the same sample at various temperatures; each curve at a fixed temperature was obtained by reversing the field direction. It can be seen that above the ordering temperature T_m=5 K the Hall voltage varies almost linearly with the applied field ---- a normal Hall effect. Once the temperature is lowered to below T_m, the behavior turns out to be different, in which an initial increment in the Hall voltage at weak field is followed by a linear and ordinary portion at high field. It is likely that the field position at which the initial and final portions are separated tends to shift to a higher field as the temperature is decreased. Such behavior may be surely reminiscent of an extraordinary Hall effect observed in ferromagnetic materials; it has been

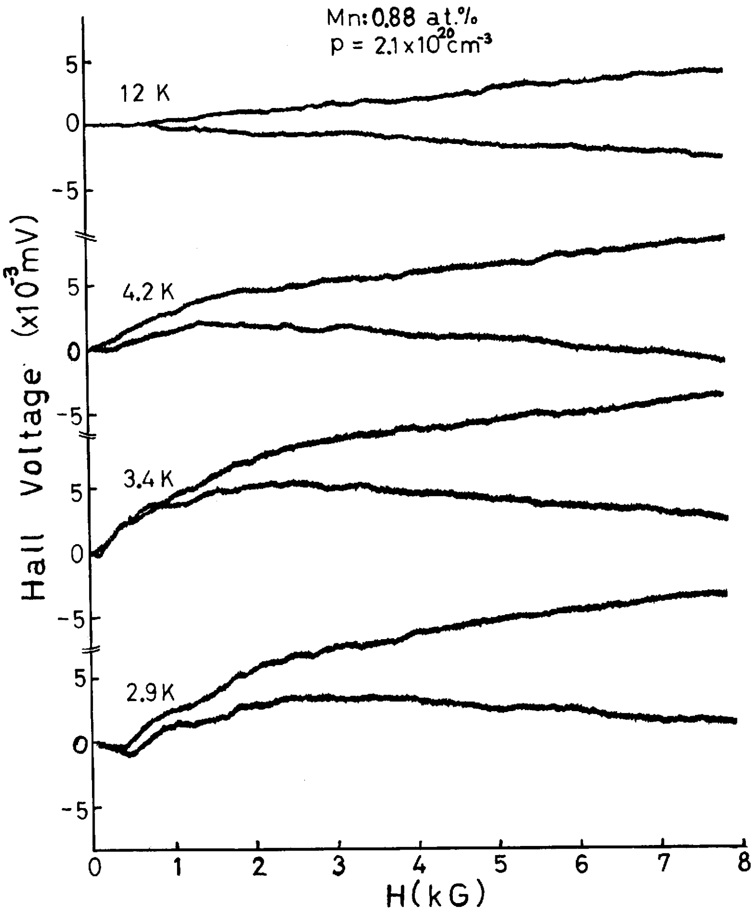

Fig. 5. Recorded traces of the Hall voltages for the same sample as in Fig. 3 against the magnetic field at various temperatures, each curve corresponding to the one and reversed direction of the applied field.

well established for long that there is a contribution to the Hall field depending on the state of magnetization of the specimen. In the following we take only a brief and qualitative look at the effect in ferromagnets, along with the present results.

The Hall effect in ferromagnetic materials is given by the phenomenological relation[3)]

$$E = R_o H + R_1 M,$$

where E is the Hall field per unit current density, R_o the ordinary Hall coefficient, H the external magnetic field, and M the macroscopic magnetization of the sample. R_1 is called the extraordinary Hall coefficient. For ferromagnetic thin films a graphical analysis of the experimental results was made to yield the constants R_o, R_1, and saturation magnetization M_s.[4] Here we do not intend to carry out a numerical evaluation, but it is worth noting that in our degenerate semiconductor doped with magnetic impurities there exists the extraordinary Hall effect when the temperature is below the magnetic ordering temperature and that the similarity of the behavior to ferromagnets indicates the existence of a certain amount of magnetization in this system, in which the ferromagnetic ordering is due to the indirect exchange interaction via conduction carriers.

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